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Simulation Study of a System for Measuring Directivity Index

LYNN B. POCHÉ

Methods and Systems Branch
Underwater Sound Reference Division

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NAVAL RESEARCH LABORATORY
Underwater Sound Reference Division
P. O. Box 8337, Orlando, Florida 32806

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Abstract

In a proposed directivity-index-measuring system, a semicircular array of hydrophones samples the acoustic power output of an underwater electroacoustic transducer; associated analog electronic circuitry and a digital computer yield a number representing the directivity index. The response of such a system to changes in geometric distribution of sampling points, number of points sampled, and complexity of directivity pattern has been studied by means of a computer-simulated model. Results show that the specified accuracy ±0.1 dB can be exceeded by using 11 hydrophones arranged to sample 396 equal areas of a spherical surface when the source is a plane, circular piston ($ka \leq 10$) radiating in an infinite baffle. Limits consistent with the required accuracy also were established for potential sources of error within the system (projector misalignment, finite sampling time, dynamic range, and conversion nonlinearity).

Problem Status

This is an interim report on the problem.

Problem Authorization

NRL Problem S02-30

Project RF 05-111-401-4471

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Contents

Illustrations

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SIMULATION STUDY OF A SYSTEM FOR MEASURING DIRECTIVITY INDEX

Introduction

Because directivity index is a necessary factor in determining other important characteristics of a transducer, it is a commonly measured quantity. It is required, for example, in the solution of the sonar equations [1] because, when a sonar is receiving, the background level at the hydrophone terminals due to isotropic noise is reduced by an amount equal to the directivity index. It is required also in the usual method for determining the efficiency of a projector. Both the measurements and the computations for finding the value of the directivity index have been time-consuming and tedious, however. For this reason, a new procedure for determining it automatically has been proposed at the Underwater Sound Reference Division, and certain requirements of the proposed system have been studied by computer simulation.

By definition, directivity index is

$$D_i = 10 \log_{10}(I_{ax}/I_{ref}), \tag{1}$$

where I_{ax} is the acoustic intensity in a specified direction (usually along the acoustic axis) and I_{ref} is the intensity that would be produced in the same direction if the radiator were replaced by a point source radiating the same total acoustic power [2]. This definition implies that, to obtain the directivity index, the total radiated acoustic power must be measured. The relation of intensity to the total power W radiated by a point source and measured at distance r is

$$I_{ref} = W/4\pi r^2.$$

Inasmuch as pressure is the parameter commonly measured, and

$$I_{ax} = p_{ax}{}^2/\rho c,$$

the directivity index of Eq. (1) becomes

$$D_i = 10 \log_{10}(4\pi r^2 p_{ax}{}^2/\rho c W), \tag{2}$$

where p_{ax} is the sound pressure produced by the radiator at the distance r in the specified direction and ρc is the characteristic impedance of the medium.

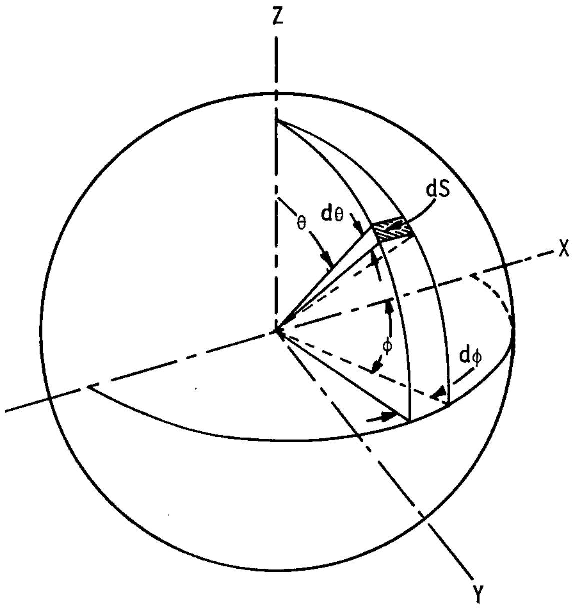

Fig. 1. Coordinate system for defining incremental surface area dS.

The total power W is found by summing the intensities over the surface S of the sphere of radius r. From Fig. 1, the area of an incremental surface is

$$dS = r^2 \sin\theta \, d\theta \, d\phi .$$

Then,

$$dW = I(dS) = (p^2/\rho c)dS = p^2 r^2 \sin\theta \, d\theta \, d\phi/\rho c ,$$

$$W = (r^2/\rho c) \int_0^{2\pi} \int_0^{\pi} p^2(\theta,\phi) \sin\theta \, d\theta \, d\phi . \qquad (3)$$

Substituting Eq. (3) into Eq. (2) gives

$$D_i = 10 \log_{10} \left[4\pi p_{ax}^{\ 2} \Big/ \int_0^{2\pi} \int_0^{\pi} p^2(\theta,\phi) \sin\theta \, d\theta \, d\phi \right] . \qquad (4)$$

What is required, then, is one pressure measurement p_{ax} on the specified axis, and a sufficient number of pressure measurements $p(\theta,\phi)$ to approximate closely the total radiated power.

The Proposed System

Several devices for measuring directivity index have been described in the past [3-6], but either they have been unable to produce a value for D_i in a single pass of the rotator, or, as analog signal devices, they are rather slow in operation. In some instances, both objections apply. The precision of those methods that require graphical computation is extremely limited.

In the system proposed here, the sampling sphere would be described by placing the projector at the center of curvature of a semicircular array of hydrophones and rotating the projector in a plane normal to the plane of the array. This produces the same relative motion as rotating the array around a line through the end points, with the projector at the center. As the projector is rotated, the outputs of the hydrophones in the array would be sampled. After being converted, the sampled values would be digitized and stored in a digital computer programmed to provide the value of D_i. If desirable, the system could be operated off-line to the computer, the output being a paper tape containing the digitized hydrophone outputs along with appropriate information indicating the channel number, rotator angle, and gain settings. A flow chart for a possible D_i computation is shown in Appendix A.

The problem that must be addressed is, then, "How closely must the spherical space be sampled to provide D_i to a specified accuracy?" The answer will determine the number of hydrophones in the array, the number of channels in the system, the time required to perform the measurement, the cost, and other parameters.

Simulation of System

It was decided to evaluate the proposed system by simulating its performance on a computer while changing the appropriate system parameters, then defining their limits by observing the variations in performance.

The simulation model adopted consisted of an array of N hydrophones (N being odd) distributed symmetrically in a semicircle about a plane circular piston in an infinite baffle. The number of hydrophones in the array must be odd to make the on-axis measurement p_{ax}. The plane circular piston in an infinite baffle meets the requirement that the source simulate the directivity characteristics of a typical transducer. Moreover, it has a fairly simple analytical function for pressure:

$$p(\theta) = \frac{2J_1(ka \sin \theta)}{ka \sin \theta},$$

where $J_1(\ )$ is a Bessel function of order one for cylindrical coordinates,

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$k = 2\pi/\lambda$ is the wave number, a is the radius of the piston, and λ is the wavelength of sound in the medium at the specified frequency. Because the assumed source can radiate only into half-space, the model array was rotated through $\pm 90^{\circ}$ about the acoustic axis of the piston.

The following system parameters were introduced into the simulation model as variables:

- distribution of hydrophones
- number of hydrophones
- array rotation increment
- the value of ka

The assumed accuracy of measurement required was ±0.1 dB.

It was apparent that the number of hydrophones might depend on the way they would be distributed around the array. Spacing the hydrophones uniformly around the semicircle would result in an "equal-angle" distribution. As can be seen from Eq. (3), if the spherical space is sampled as a function of θ (that is, by equal angles), a $\sin\theta$ term is introduced into the summation.

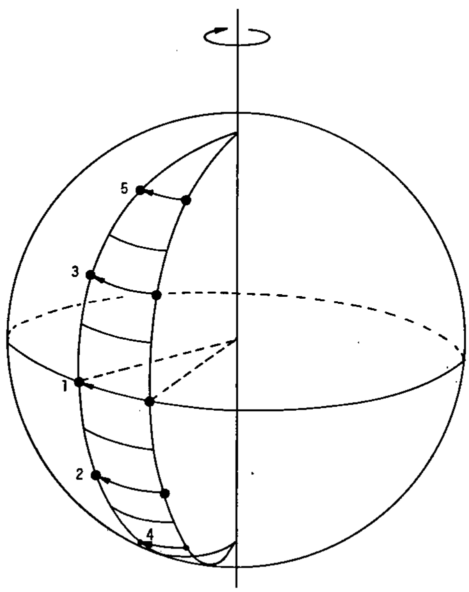

Fig. 2. Arrangement of hydrophones for equal-area sampling.

An alternative method would be to arrange the hydrophones as in Fig. 2, so that, as the array is rotated through an angular increment, each hydrophone sweeps a zone of equal area on the sphere. If the sampling is done as a function of area,

$$W = (r^2/\rho c) \sum_{m=1}^{360/\Delta\phi} \sum_{n=1}^{N} p^2(n,\phi_m) ,$$

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where N is the number of array hydrophones, $\Delta\phi$ is the rotation angle between readings, and $\phi_m = (m - 1)\Delta\phi$.

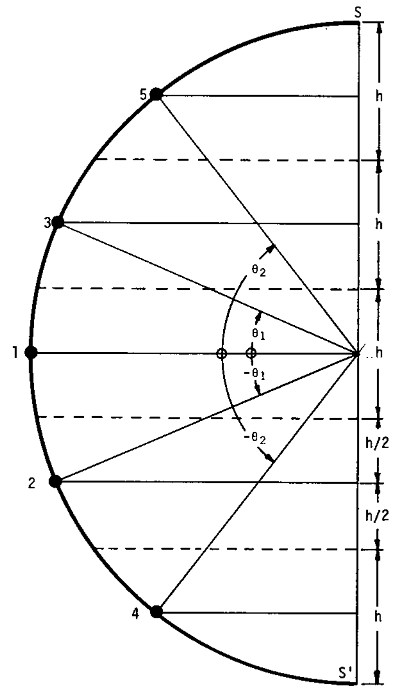

Fig. 3. Distribution of 5 hydrophones for equal-area sampling.

Figure 3 shows the distribution required to sample equal areas with five hydrophones. Because zones of equal area on a sphere are of equal height, the diameter SOS', Fig. 3, can be divided into five parts of height h. If the hydrophones are to be located at the centers of the zones, their positions will be determined by the projections of the centers of these five segments h on the semicircle representing the array. It is clear that

$$h = 2\overline{OS}/N,$$

$$\sin\theta_1 = h/\overline{OS} = 2/N,$$

$$\sin\theta_2 = 2h/\overline{OS} = 4/N,$$

and

$$\sin\theta_n = nh/\overline{OS} = 2n/N,$$

whence

$$\theta_n = \sin^{-1}(2n/N).$$

"Equal-area" distribution angles for arrays of three to 23 hydrophones are listed in Appendix B.

The theoretical value of D_i for the piston source in the model can be computed in closed form [7] for a specified value of ka from the equation

$$D_i = \frac{10\log_{10}(ka)^2}{1 - 2[J_1(2ka)]/2ka}.$$

For ka = 10.000, D_i = 20.029 dB. Beranek [8] illustrates the variation of directivity pattern as ka is changed. To produce a pattern with important side-lobe structure, the value ka = 10 was assigned.[1] It will be shown that the lower the numerical value of ka, the smaller the number of hydrophones required to produce a specified measurement accuracy.

Besides varying the system parameters, several potential sources of error in the system were examined to assess their effect on measurement

[1]For a 2-in.-diam piston, this corresponds to the frequency 95 kHz.

accuracy. These sources of error were:

- misalignment of the projector
- finite sampling time
- noise level or dynamic range
- nonlinearity of the a-c/d-c converter

"Misalignment" refers to noncoincidence of the acoustic axis of the projector and the line joining the array center with the 0° or reference hydrophone (Fig. 4). It is assumed that, in practice, the projector would be raised or lowered until the reference hydrophone 1 indicated maximum output. The angular misalignment of the array projector is represented by the small angle M in Fig. 4.

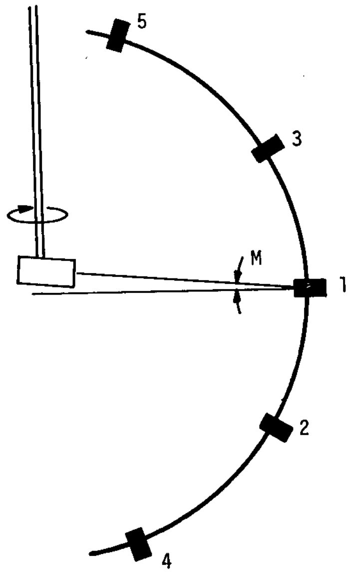

Fig. 4. Misalignment of acoustic axis.

The other three error sources listed are in the electronics system and are associated with the performance requirements of a single circuit--the a-c/d-c converter. To derive a number that represents the magnitude of the electrical output of the hydrophones, the alternating signal will be rectified and averaged, and the resulting d-c voltage will be digitized. The total time required depends on the constants of the charging circuit and the accuracy specified. One method is to use a peak-detector circuit that requires only a few cycles of the input signal to give a stable measurement. The output can be calibrated to indicate rms voltage, and will rely on the quality of the sinusoidal input for accuracy.

Two models were used to simulate these three sources of error. In the first, it was assumed that the linear amplitude conversion function of the converter was perfect; a noise floor expressed as dynamic range in dB was introduced to limit the lower level of signal amplitude. In addition, the time required by the converter to sample the signal was introduced as a "skew error" in degrees. Because this representation simulates continuous rotation during sampling, a spread in sampling time becomes a spread in rotation. In the simulation, this meant that the largest value of pressure encountered within the angular sector defined by the skew angle was used to represent the increment of area rather than the value at the center of the area.

In the second model, the same representation of sampling time was retained and a third-degree polynomial was used to approximate the nonlinear conversion characteristic of an experimental a-c peak-detector circuit.

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Programs and Result of Simulation

One main program and an overlay program were written in TIME-SHARING FORTRAN to determine the method of distribution and the number of hydrophones. These programs were named =AREA and =ANGLE. Three other overlay programs were called MALIGN, SKU/DR, and SKU/AC. All of these programs appear in Appendix C. All values in the programs and tables are based on the simulation models defined previously. Some results of program runs are shown in Table 1, Appendix D. The minimum acceptable values within the ±0.1-dB-error limit are indicated. The "equal-area" distribution seems to be the more economical way to sample the spherical surface, requiring only 7 hydrophones sampling every 15° of rotation for ka = 10. To check the requirements at lower wave numbers, several runs were made for ka = 7 and ka = 5. These results are given in Tables 2 and 3.

Because other sources of error also must be considered, some margin was allowed in the number of hydrophones used. It was decided to fix the number of hydrophones at 11 and the rotation increment at 10° for an equal-area array.

The results of program changes required to simulate the projector-array misalignment problem are shown in Table 4. If no other error sources were considered, a misalignment of 12° could be tolerated. The more likely maximum value 5° produces less than 0.02 dB error, so it appears that this could be tolerated along with other errors.

The program overlay SKU/DR shows the simulation of sampling error and changes in dynamic range. The skew angle was varied from 0 to 3° and the dynamic range was varied from 100 to 25 dB. Once a value for array rotation rate has been specified, skew angle can be expressed as sampling time. If, for example, we desire that the period for making a complete measurement be 5 min, the rotation rate will be 360°/300 sec = 1.2°/sec. If 11 channels must be read in a 10° rotation increment, or in 12 sec, then only 1.1 sec per channel is allowed by the rotation rate. This requires that the electronic circuit convert and digitize the signal in 1.1 sec, a resonable requirement at frequencies above 10 Hz. The results shown in Table 5 indicate that a dynamic range of not more than 30 dB is required for this rotation rate.

The next simulation involved sampling error and linearity of the a-c/d-c converter (SKU/AC). The coefficients of the polynomial that approximates the conversion function are used in lines 272-273. The results of SKU/AC are listed in Table 6. Using 1.5° sampling span, the converter error still is within the ±0.1-dB-error limit.

Conclusions

The directivity index of a transducer can be measured to within ±0.1 dB in one pass of continuous rotation by an array of eleven hydrophones placed so as to divide the described sphere into 396 equal areas when measurements are made every 10° of rotation. It is assumed that the directional characteristics of the transducer are not more complex than those of a plane piston of radius 1.59λ (ka = 10) radiating in an infinite baffle.

If the period required to make a complete measurement is 5 min, the dynamic range of the system need not be greater than 30 dB. Five minutes has been shown to be consistent with the linear accuracy and response time of a-c/d-c converters that have been constructed at the USRD.

Acknowledgments

The idea for the system described was suggested by Mr. Claude C. Sims. The author gratefully acknowledges discussions with Mr. Gerald A. Sabin throughout the study.

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3. *Completion Report on Transducer Calibration Facilities and Techniques of UCDWR*, University of California Division of War Research Report No. U435 (1946), p. 21.

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5. C. E. Green and J. R. Roshon, "Directivity Factor Computer," J. Acoust. Soc. Amer. 35, 792(A) (1963).

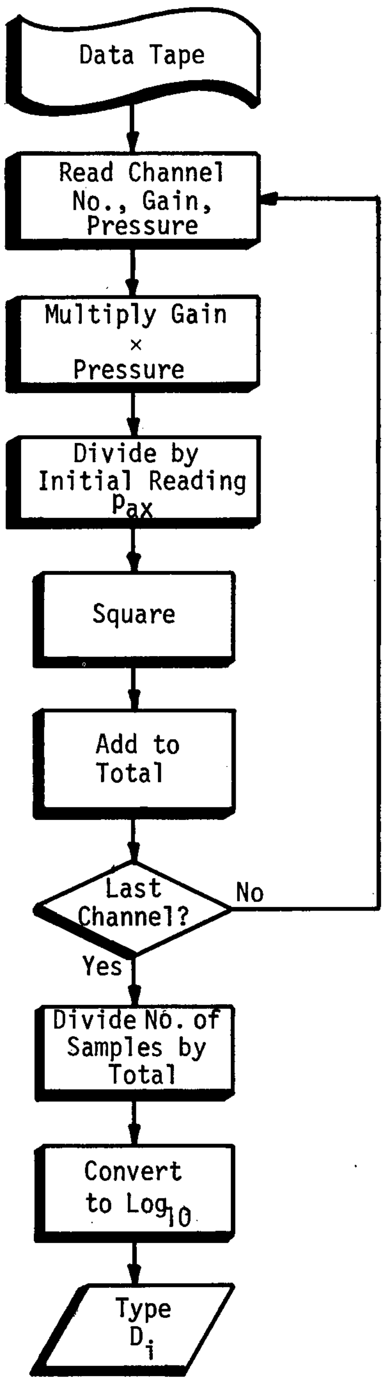
6. *Basic Methods for the Calibration of Sonar Equipment*, Summary Technical Report of NDRC, Div. 6, Vol. 10 (1946), Sec. 4.1.3.

7. L. E. Kinsler and A. R. Frey, *Fundamentals of Acoustics* (John Wiley and Sons, Inc., New York, 1962), 2nd ed., p. 174.

8. Reference 2, Fig. 4.10.

Appendix A

Flow Chart for Reduction of Directivity Index Data



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Appendix B

Angular Position of Hydrophones for Equal-Area Sampling With 3 to 23 Hydrophones

3	5	7	9
0.00 deg	0.00 deg	0.00 deg	0.00 deg
±41.81	±23.58	±16.60	±12.84
	±53.13	±34.85	±26.39
		±59.00	±41.81
			±62.73

11	13	15	17
0.00	0.00	0.00	0.00
±10.48	±8.85	±7.66	±6.76
±21.32	±17.92	±15.47	±13.61
±33.06	±27.49	±23.58	±20.67
±46.66	±37.98	±32.23	±28.07
±65.38	±50.28	±41.81	±36.03
	±67.38	±53.13	±44.90
		±68.96	±55.44
			±70.25

19	21	23
0.00	0.00	0.00
±6.04	±5.47	±4.99
±12.15	±10.98	±10.02
±18.41	±16.60	±15.12
±24.90	±22.39	±20.35
±31.76	±28.44	±25.77
±39.17	±34.85	±31.45
±47.46	±41.81	±37.50
±57.36	±49.63	±44.08
±71.33	±59.00	±51.50
	±72.25	±60.41
		±73.04

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Appendix C

FORTRAN Program and Overlays for Evaluation of Simulated Arrays

```
=AREA

100 DIMENSION XJ(10)
110 20 PRINT "KA"
120 PRINT "NO. OF HYDROPHONES IN ARRAY"
130 PRINT "ARRAY ROTATION INCREMENT"
140 INPUT,CKA,HYD,ROT
150 PI=4.*ATAN(1.)
160 RSUM=0.
170 DO 50 BETA=0,90,ROT
180 RBETA=BETA
190 RBETA=RBETA*PI/180.
200 ASUM=0.;IHYD=HYD
210 DO 40 I=0,IHYD,2
220 T=I
230 Z1=CKA*SQRT(SIN(RBETA)↑2+(T/HYD)↑2*COS(RBETA)↑2)
240 IND=1;ORD=1;X=Z1
250 CALL BESL(IND,ORD,X,XJ)
260 IF(Z1) 41,41
270 PRES=2.*XJ(1)/Z1
280 GOTO 42
290 41 PRES=1.
300 42 PRESQ=PRES↑2
310 IF (T) 43, 43, 44
320 43 PRESQ=PRESQ/2.
330 44 ASUM=ASUM+PRESQ
340 40 CONTINUE
350 IF (89-BETA) 51
360 IF (BETA) 51,51
370 GOTO 52
380 51 ASUM=ASUM/2.
390 52 RSUM=RSUM+ASUM
400 50 CONTINUE
410 DIR=HYD*(90./ROT)/RSUM
420 DI=10./LOG(10.)*LOG(DIR)
430 PRINT 90, "DI=", DI, "DB"
440 90 FORMAT (F14.6)
450 GOTO 20
460 STOP;END
470 $USE BESLX$***
480 $USE GAMXX$***
```

Program Overlay for =ANGLE

```
225 TT=T*PI/2./HYD
230 Z1=CKA*SQRT(SIN(RBETA)↑2+COS(RBETA)↑2*SIN(TT)↑2)
300 42 PRESQ=PRES↑2*COS(TT)
410 DIR=(HYD*180.)/(ROT*PI)/RSUM
```

Program Overlay for MALIGN

```
131 PRINT "MISALIGNMENT"
140 INPUT,CKA,HYD,ROT,ALN
205 IHYDM=-1*IHYD+1
210 DO 40 I=IHYDM,IHYD,2
225 ANGL=ATAN(T/HYD/SQRT(1.-(T/HYD)↑2))+ALN*PI/180.
230 Z1=CKA*SQRT(SIN(RBETA)↑2+COS(RBETA)↑2*SIN(ANGL)↑2)
310
320
410 DIR=HYD*(180./ROT)/RSUM
```

Program Overlay for SKU/DR

```
131 PRINT "SKEW"
132 PRINT "DYNAMIC RANGE"
140 INPUT,CKA,HYD,ROT,SKEW,DYNR
145 DNOISE=1./EXP(DYNR/(20./LOG(10.)))
191 SK=SKEW*PI/180.
201 IF(RBETA)101,101,102
202 101 SK=0.
203 102 RBETAP=RBETA+SK/2.
204 RBETAM=RBETA-SK/2.
230 Z1=CKA*SQRT(SIN(RBETAP)↑2+(T/HYD)↑2*COS(RBETAP)↑2)
255 PRESP=XJ(1)
256 Z4=CKA*SQRT(SIN(RBETAM)↑2+(T/HYD)↑2*COS(RBETAM)↑2)
257 IND=1;ORD=1.;X=Z4
258 CALL BESL(IND,ORD,X,XJ)
259 PRESM=XJ(1)
260 IF(ABS(PRESP)-ABS(PRESM))110,120,120
261 110 PRES=PRESM
262 Z1=Z4
263 GOTO 150
264 120 PRES=PRESP
265 IF(Z1)41,41
270 150 PRES=2.*PRES/Z1
271 PRES=ABS(PRES)
272 IF(DNOISE-PRES)42,42
273 PRES=DNOISE
```

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Program Overlay for SKU/AC

```
131 PRINT "SKEW"
140 INPUT,CKA,HYD,ROT,SKEW
191 SK=SKEW*PI/180.
201 IF(RBETA)101,101,102
202 101 SK=0.
203 102 RBETAP=RBETA+SK/2.
204 RBETAM=RBETA-SK/2.
230 Z1=CKA*SQRT(SIN(RBETAP)↑2+(T/HYD)↑2*COS(RBETAP)↑2)
251 PRESP=XJ(1)
252 Z4=CKA*SQRT(SIN(RBETAM)↑2+(T/HYD)↑2*COS(RBETAM)↑2)
253 IND=1;ORD=1;X=Z4
254 CALL BESL(IND,ORD,X,XJ)
255 PRESM=XJ(1)
256 IF(ABS(PRESP)-ABS(PRESM))110,120,120
257 110 PRES=PRESM
258 Z1=Z4
259 GOTO 150
260 120 PRES=PRESP
265 IF(Z1)41,41
270 150 PRES=2.*PRES/Z1
271 PRES=ABS(PRES)
272 PRES=-.43856849E-02+.10525747E+01*PRES-.80028461E-01*PRES↑2
273 ++.40756408E-01*PRES↑3
```

Appendix D

Table 1. Computed values of directivity index in decibels. Equal-angle and equal-area sampling arrays; ka = 10; true D_i = 20.029 dB.

Number of Hydrophones	Array Rotation Increment 5°	10°	15°	22.5°
Equal Angle				
23	20.029	20.029	20.026	19.341
15	20.029		20.026	19.341
11	20.008	20.008	20.005*	19.322
9	19.733			
7	18.652		18.650	18.085
Equal Area				
23	20.029		20.026	19.340
19	20.029			
13	20.028			19.340
9	20.028		20.025	
7	20.033	20.033	20.031*	19.345
5	19.108	19.108	19.105	
3	17.280			

*Value of D_i that will meet specified error tolerance with minimum number of hydrophones and maximum rotational increment.

Table 2. Computed values of directivity index in decibels. Equal-area sampling array; ka = 7; true D_i = 16.986 dB.

Number of Hydrophones	Array Rotation Increment 5°	10°	15°	22.5°	30°
23	16.986		16.986	16.969	16.592
15		16.986		16.969	
7		16.988		16.971	16.595
5		17.005		16.988*	16.610
3		15.367			

*Value of D_i that will meet specified error tolerance with minimum number of hydrophones and maximum rotational increment.

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Table 3. Computed values of directivity index in decibels. Equal-area sampling array; ka = 5; true D_i = 14.017 dB.

Number of Hydrophones	Array Rotation Increment 5°	15°	22.5°	30°	45°
23	14.018	14.018	14.017	14.002	13.448
15	14.018				
9	14.019				
5	14.021	14.021	14.018	14.005*	13.450
3	13.921	13.921	13.921	13.904	13.336

*Value of D_i that will meet specified error tolerance with minimum number of hydrophones and maximum rotational increment.

Table 4. Effect of misalignment of acoustic axis; ka = 10; 11 array hydrophones; array rotation increment, 10°; true D_i = 20.029 dB.

Misalignment (deg)	Directivity Index (dB)
0	20.028
1	20.029
2	20.030
4	20.038
5	20.043
6	20.050
8	20.067
12*	20.116
13	20.132

*Maximum misalignment that will provide D_i meeting specified error tolerance.

Table 5. Effect of skew angle and dynamic range (in decibels). Plane circular piston projector; ka = 10; 11 array hydrophones; array rotation increment, 10°; true D_i = 20.029 dB.

Dynamic Range (dB)	Skew Angle 0°	1.0°	1.5°	2.0°	2.5°	3.0°
100	20.028	20.003	19.987	19.969	19.949	19.927
40	20.027					19.926
35				19.963	19.943	19.921
30	19.972	19.951	19.938*	19.923	19.904	
25	19.725	19.714	19.706	19.697		

*Value of D_i that will meet specified error tolerance with minimum dynamic range and maximum skew.

Table 6. Effect of skew angle and nonlinear signal conversion. Plane circular piston projector; ka = 10; 11 array hydrophones; array rotation increment, 10°; true D_i = 20.029 dB.

Skew Angle (deg)	Directivity Index (dB)
0	19.985
1.0	19.959
1.5*	19.943
2.0	19.925

*Maximum allowable skew angle that will provide D_i within specified tolerance with the conversion characteristics of the experimental a-c peak-detector circuit used.

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13. ABSTRACT

In a proposed directivity-index-measuring system, a semicircular array of hydrophones samples the acoustic power output of an underwater electroacoustic transducer; associated analog electronic circuitry and a digital computer yield a number representing the directivity index. The response of such a system to changes in geometric distribution of sampling points, number of points sampled, and complexity of directivity pattern has been studied by means of a computer-simulated model. Results show that the specified accuracy ±0.1 dB can be exceeded by using 11 hydrophones arranged to sample 396 equal areas of a spherical surface when the source is a plane, circular piston ($ka \leq 10$) radiating in an infinite baffle. Limits consistent with the required accuracy also were established for potential sources of error within the system (projector misalignment, finite sampling time, dynamic range, and conversion nonlinearity).

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Simulation						